NASA CR-132835

INVESTIGATION OF ULTRAVIOLET INTERSTELLAR EXTINCTION

Grant NGR 09-015-200

Semiannual Progress Report No. 1

For the period 1 October 1972 to 31 March 1973

Principal Investigators

Dr. Cecilia Payne-Gaposchkin

Mrs. Katherine L. Haramundanis

Prepared for

National Aeronautics and Space Administration

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ABSTRACT

To describe most succinctly the progress we have made during the past 6 months in utilizing Celescope OAO-2 data in a study of extinction, we have prepared an outline of the work, with conclusions drawn from each inquiry. Where further investigation seems fruitful, we have so indicated. Every item has been or will be covered in further detail in research publications or reports.

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1. STATISTICAL STUDIES OF THE DATA

1.1 Analysis of Celescope Data

A. Frequency analysis of all Celescope observations in cameras 1 and 3 revealed that the number of observations per unit area of each camera has a maximum in the U_2 passband and a discontinuity between the U_1 and the U_2 passbands. In camera 1, the discontinuity occurs at $\eta = 0.0$; in camera 3, at $\eta = -0.2$.

B. Examination of the zero-point setting of the Celescope magnitudes made it possible for us to evaluate its potential uncertainty. This uncertainty is a combination of the error of $E(B-V)$ and of $E(U_i - V)$ and of the assumption that extinction in $B-V$ is directly correlated with extinction in $U_i - V$. We found the potential uncertainty of the zero-point setting in each passband to be as follows:

$$U_1 = \pm 0.12 \quad , \quad U_2 = \pm 0.79 \quad , \quad U_3 = \pm 0.03 \quad , \quad U_4 = \pm 0.99 \quad .$$

We hypothesize that since some of these values are much larger than the expected error of Celescope and UBV data (± 0.25), the variation indicates that $E(B-V)$ is not directly correlated with $E(U_i - V)$.

C. Evaluation of the data observed in U_4 with short exposure times ($\leq$ 15 sec) revealed that some objects in this category were excluded from the Celescope Catalog (Davis et al., 1973). This can only mean that they are anomalously bright in U_4. An example is 30 Doradus (see Figure 1). We hope to have an opportunity to examine such objects more fully (Haramundanis and Payne-Gaposchkin, 1973).

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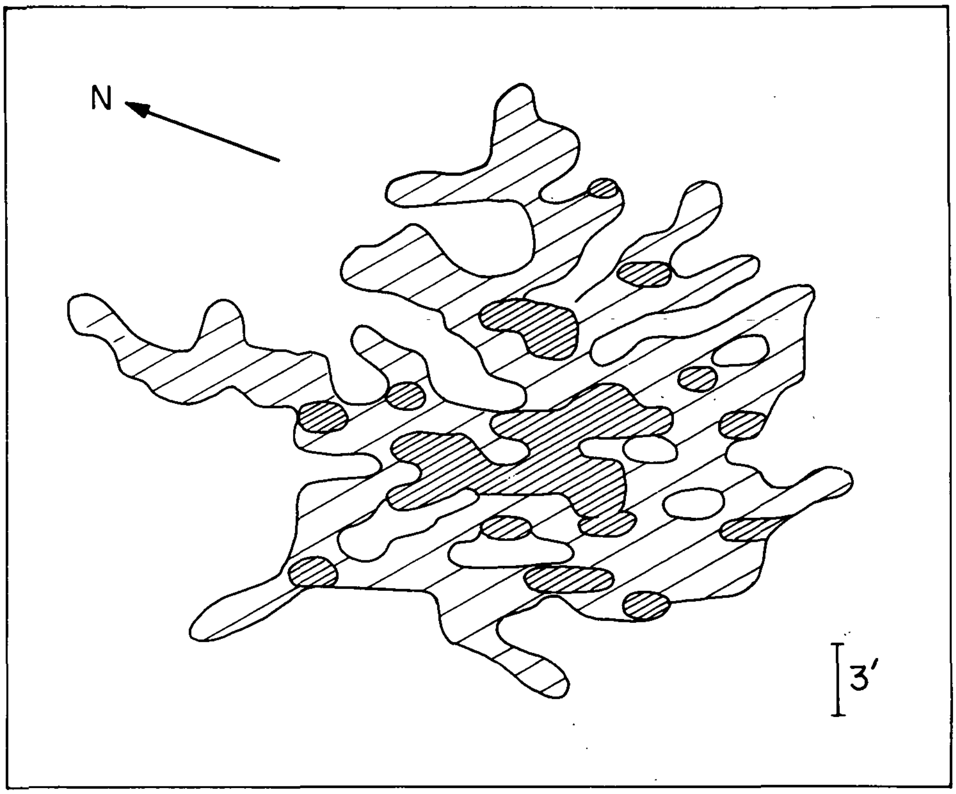

Figure 1. 30 Doradus in the U_4 passband (λ = 1500 Å).

1.2 Analysis of UBV Data from the Photoelectric Catalogue

A. To make full use of the UBV data available for 15% of the Celescope data, we analyzed the data from the Photoelectric Catalogue (Blanco et al., 1968). We first made a frequency analysis and cross correlation of the number of observations per reference in this publication. Of 429 references, 156 had more than 30 observations in common with some other reference. An analysis of the observations made it possible for us to make a realistic assessment of the systematic errors of UBV data.

B. To assess the random errors of the UBV data, we tallied the mean standard deviation for all the stars in the Catalogue for which more than one observation was given. The results for each parameter were $\bar{\sigma}_{(B-V)} = \pm 0.03$, $\bar{\sigma}_{(U-B)} = \pm 0.04$, and $\bar{\sigma}_{(U_c - B)} = \pm 0.01$ (Haramundanis and Payne-Gaposchkin, 1973).

C. To assess the systematic errors of the UBV data, we computed residuals from the mean for observations in the selected 156 references. By using the t test at the 1% level, we deduced that about 20% of these data have systematic errors that are a function of apparent magnitude. These errors may be as large as 0.05 and may occur in either V, or U - B, or B - V. Usually, for a given reference, the error seems to be generated by a single parameter, such as V or B (see Figure 2).

D. More than half of the Celescope observations were made in the Southern Hemisphere. For most of these, UBV data on the system of Johnson and Morgan (1953) are nonexistent. However, data on the system used by Cousins and Stoy (1962) for southern stars are available for about 6% of Celescope objects. To utilize these, we derived an empirical relation between U - B and $U - B_c$ by extracting the appropriate data from the Photoelectric Catalogue. The relation, illustrated in Figure 3, is applicable to stars for which $U - B_c < 1.5$. We have utilized it in our derivation of intrinsic colors by the Q method (Haramundanis and Payne-Gaposchkin, 1973).

1.3 Derivation of Systematic Corrections to Non-UBV Ground-Based Data

Since we anticipate that to make full use of the Celescope data we shall employ even non-UBV data, we evaluated the systematic errors for photovisual and visual magnitudes. The relation of V to m_{pv} is a function of spectral class alone, and that of V to m_v is a function of V. The $V - m_{pv}$ may be as large as 0.05 mag, and $V - m_v$ as large as 0.35 mag (Haramundanis and Payne-Gaposchkin, 1973).

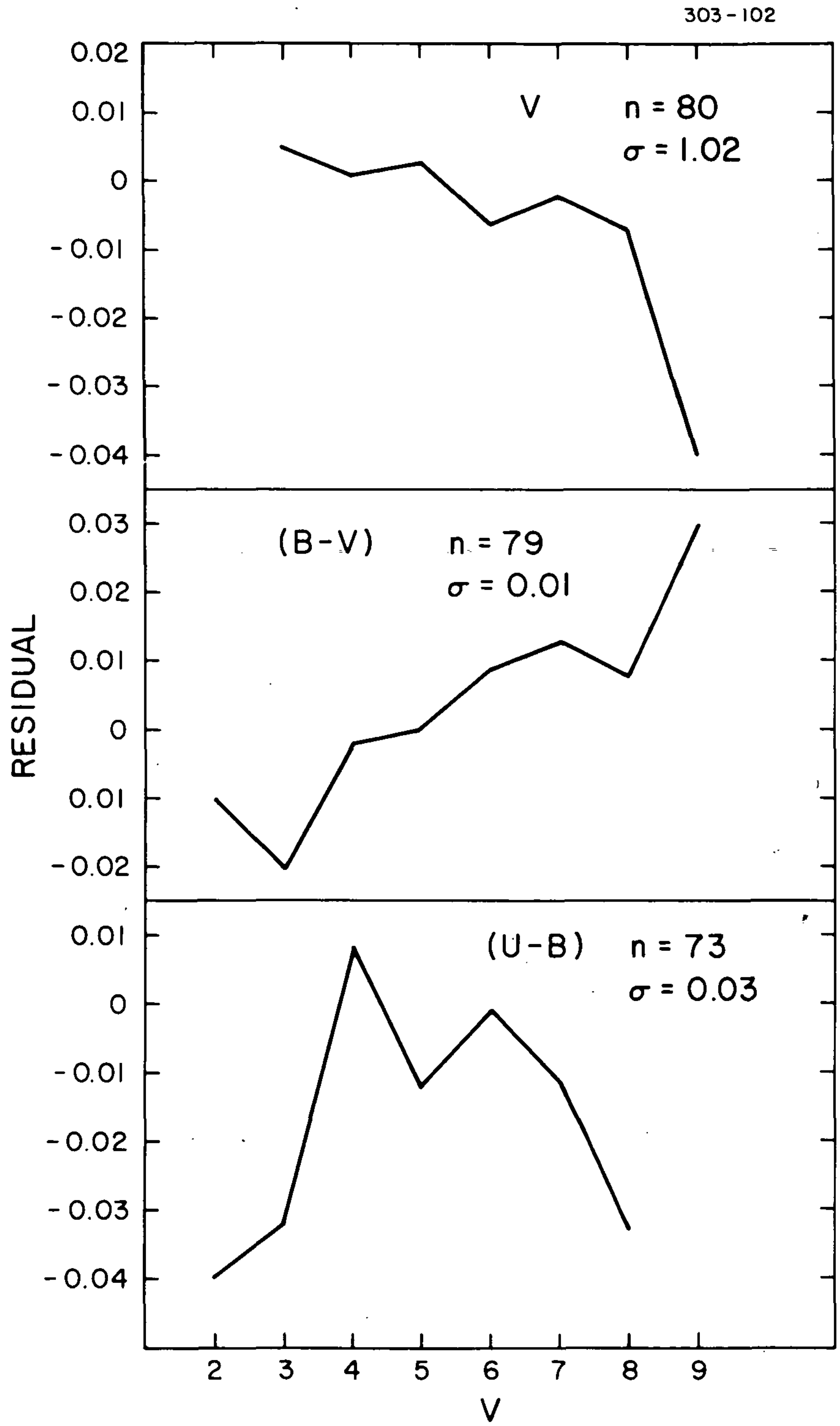

Figure 2. Systematic errors in the UBV photometry.

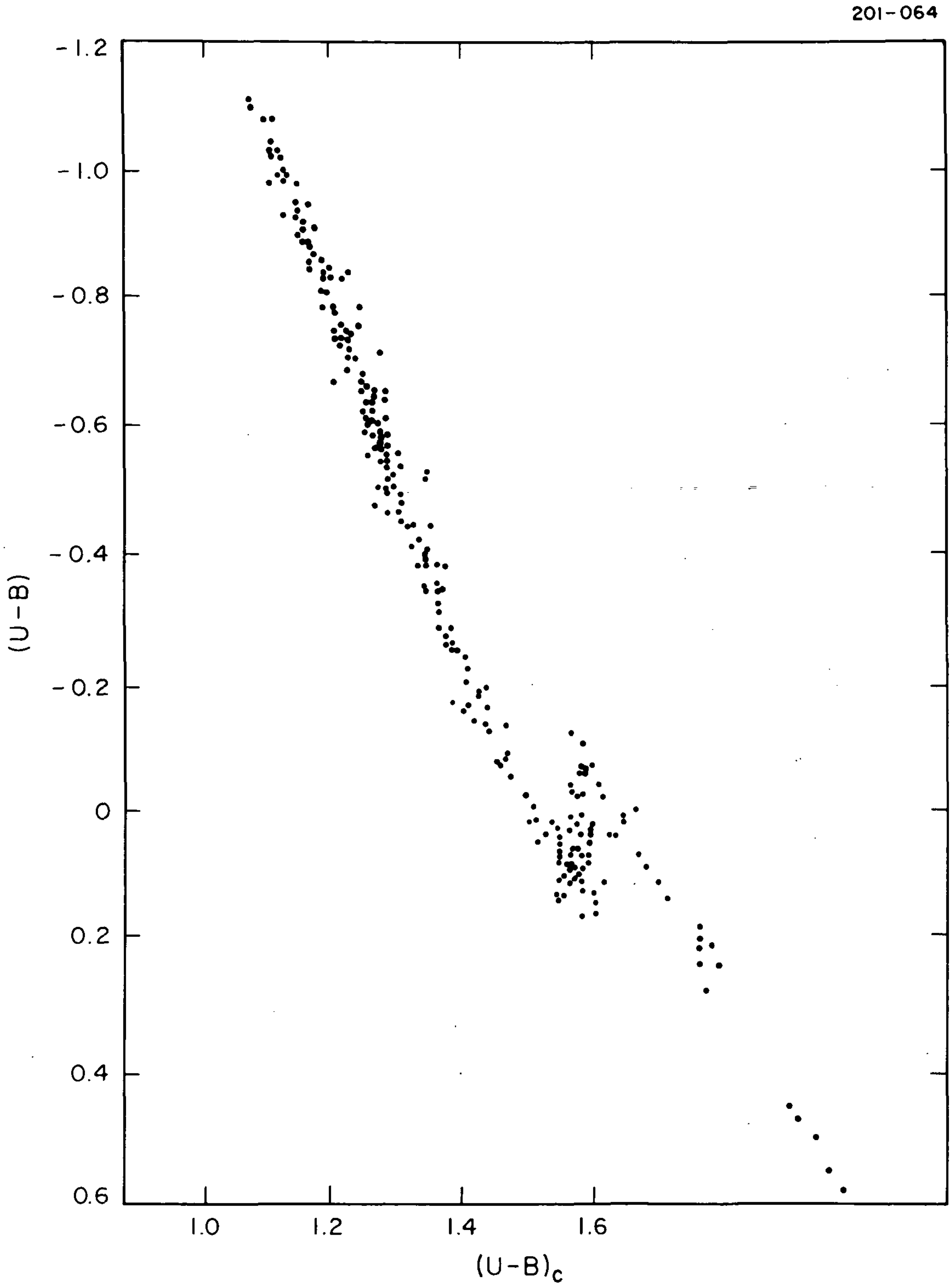

Figure 3. U - B compared with $(U-B)_c$.

2. DERIVATION OF INTRINSIC COLORS

2.1 $(B-V)_0$

A. By the simplified Q method. Johnson (1958) described both algebraically and with a nomogram the relation between the observed quantities U - B and B - V and the deduced quantity $(B-V)_0$. Unfortunately, both his equations and his nomogram contain important errors. We derived a simplified expression accurate to 0.01 for $(B-V)_0$ and utilized it for the derivation of this quantity. We used this expression only for those stars we knew to be on the main sequence and of spectral class earlier than A1. We were able to extend our computations to stars in the Southern Hemisphere by utilizing our empirical relation for the conversion of $(U-B)_c$ to U - B.

B. From MK spectral classes. For stars later than A0 and for those not on the main sequence, $(B-V)_0$ cannot be derived by the Q method. We therefore utilized the colors of Johnson (1968) for main-sequence stars and those of Serkowski (1963) for supergiants to obtain the intrinsic colors for these stars.

C. From HD spectral classes. For work on extinction, although not for the derivation of original intrinsic ultraviolet colors, it is important to extend the derivation of $(B-V)_0$ to even the faint stars in our data. For most of these, only HD spectral types are known. Once our intrinsic ultraviolet colors were derived, it was possible, on a second iteration, to examine the validity of the spectral classes from the HD. It was immediately apparent that the stars with HD spectral classes were subject to classification errors that are a function of apparent magnitude. These misclassifications may amount to as much as 5 or 6 subclasses for a star of 9th or 10th mag. We used the available UBV data to evaluate this error without recourse to the ultraviolet magnitudes (see Figure 4). Its application greatly improves the smoothness of color excesses computed on the basis of $(B-V)_0$ and $(U_i-V)_0$.

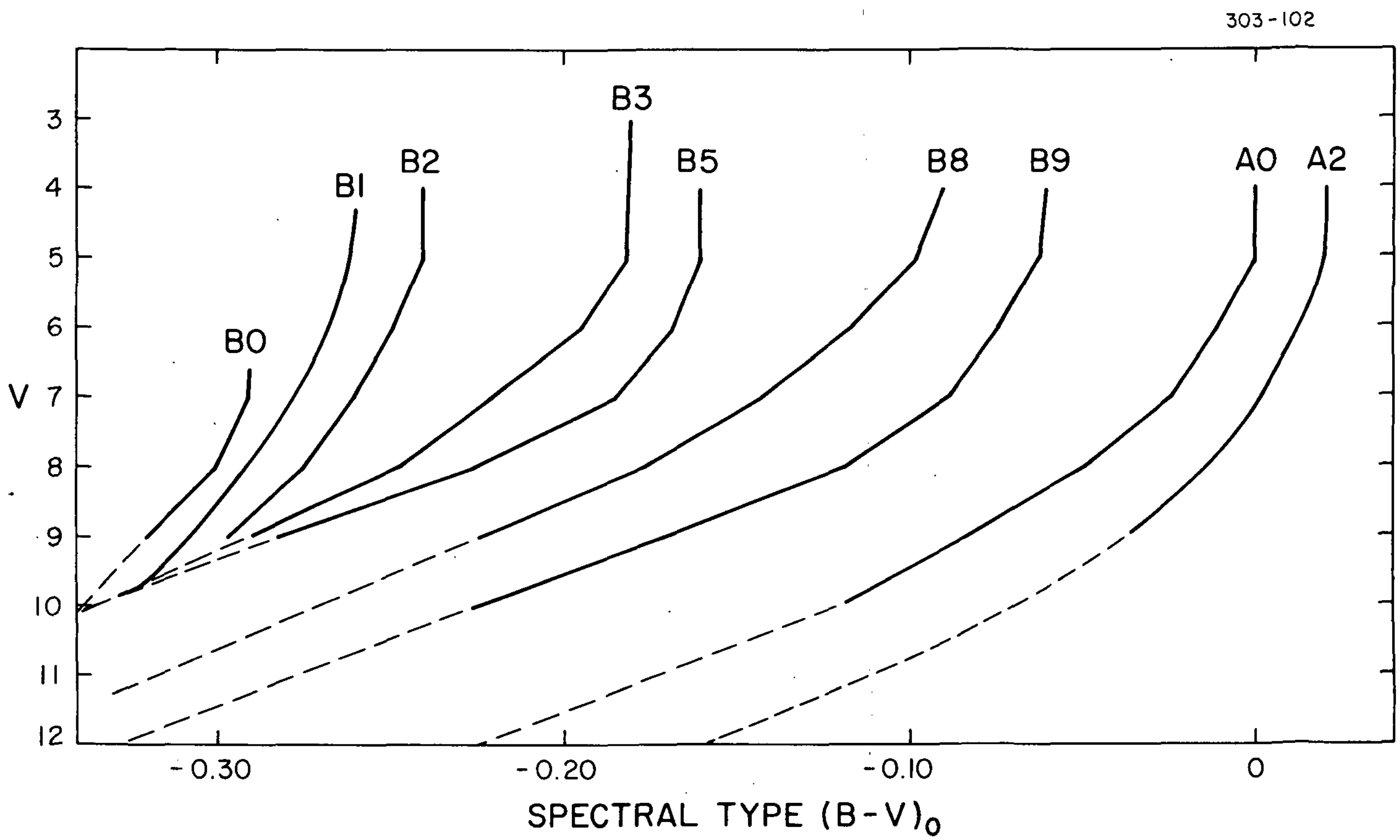

Figure 4. Systematic errors of HD spectral classifications as a function of apparent magnitude.

2.2 Derivation of $(U_i - V)_0$

A. For main-sequence stars. Since UBV and U_cBV data were available for 21% of the stars in our data, we restricted ourselves exclusively to them. Further, since we required that each star under consideration have an MK classification, we dealt only with main-sequence stars and excluded every known binary, multiple, or variable. An examination of the relation of ultraviolet color to rotation (v sin i) showed no correlation, so we made no exclusion on this basis. Using our analysis of the errors of UBV data, we further selected stars for which $E(B - V) \leq 0.04$. Of the remaining 400, we computed, for B stars, intrinsic ultraviolet colors by least squares. For stars later than A0, we utilized the colors of Johnson (1958) and of Serkowski (1963) to extend the intrinsic colors to G3 (Haramundanis and Payne-Gaposchkin, 1973).

B. For supergiants. Supergiants are of great potential interest because we may assume that among them are the most distant stars observed by Celescope. We plotted the relation of $(B - V)_0$ with $U_i - V$, using Serkowski's colors. None of the 60 stars can be considered unreddened in B - V, however, and none has ultraviolet colors less than 0.4. We deduce from the relation that their ultraviolet colors are not different from those of main-sequence stars with the same $(B - V)_0$.

2.3 Comparison of Observed and Predicted Intrinsic Ultraviolet Colors

Theoretical blanketed model atmospheres (Kurucz et al., 1973) include predictions for stars of log g = 4.0 and colors in the Celescope passbands. A comparison between our derived intrinsic colors for main-sequence stars and the predictions demonstrated that for the B stars the agreement between theory and observation is excellent, but that the A stars do not appear to be well represented by the theory (Haramundanis and Payne-Gaposchkin, 1973).

3. EXTINCTION IN THE ULTRAVIOLET

3.1 The Wavelength Dependence of $E(U_i - V)$

With the intrinsic ultraviolet colors known as a function of spectral class and $(B - V)_0$, it has been possible to compute the color excess, $E(U_i - V)$, for 80% of the stars observed by Celescope. Objects currently excluded from consideration are multiples and variables and those for which no ground-based data are available. Since fewer than 15% of Celescope observations were made with the U_1 and U_4 passbands, for the time being we have concentrated on the U_2 and U_3 passbands.

For stars on the main sequence, the average ratio of $E(U_i - V)/E(B - V)$ in U_2 is 4.7; in U_3, 5.2. Owing to the great variation in the ratios for individual stars, however, these averages are not very meaningful. For supergiants, the mean relation is not significantly different from that for main-sequence stars. This result is not in agreement with that of Laget (1973), who has analyzed photometric data on 16 stars observed with the OAO-2 Wisconsin data. Laget's result depends critically on the adopted intrinsic $(B - V)_0$ colors for supergiants.

3.2 The Wavelength Dependence of Extinction as a Function of Galactic Longitude

Since the individual ratios of $E(U_i - V)/E(B - V)$ show considerable variation, we examined them as a function of longitude at low galactic latitudes ($b^{II} \leq |\pm 5°|$). These ratios for the U_2 and U_3 passbands have minima toward the galactic center and anticenter and maxima in Carina and Cygnus (see Figure 5a, b). The relation of $E(U_3 - V)/E(U_2 - V)$ demonstrates further the longitude dependence of ultraviolet extinction and points to differences in the interstellar medium (see Figure 5c).

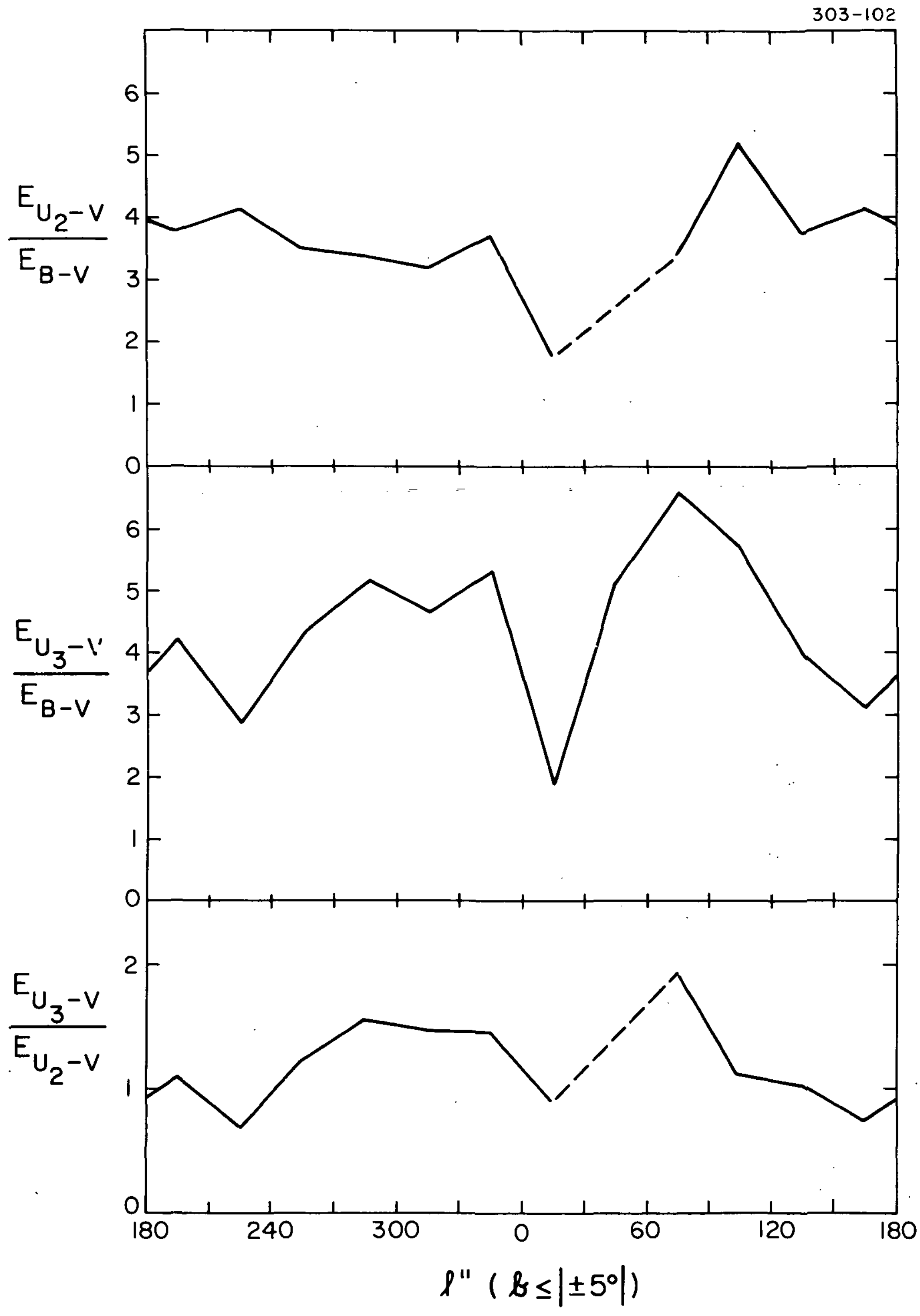

Figure 5. The variation of ultraviolet extinction with galactic longitude.

3.3 The Noncorrelation of E(B - V) with $E(U_i - V)$ in Orion

In our examination of the slopes of the reddening lines as a function of longitude, it was apparent that in the region of Orion ($200 < \ell^{II} < 210$, $-10° < b^{II} < -20°$) our attempts to find a correlation of E(B - V) with $E(U_i - V)$ resulted in a scatter diagram (see Figure 6). Further examination revealed that many of the stars had negative ultraviolet color excesses that correlated only with position, i.e., location in the Orion complex. Investigation of the radial velocities for these stars revealed that for those where more than one velocity had been measured, they were variable. This indicates that these stars are most probably multiples hitherto unresolved. For them to be so blue in the ultraviolet, the secondary component must be hotter than the primary, which is observed in the visual. Maser amplification by interstellar molecules might also explain the observed excesses, but we feel it is more likely that the objects in question are multiples.

Lee (1968) has examined some of these stars in the infrared. Comparison of his infrared excesses with our ultraviolet excesses shows that when his excesses are negative, ours are positive, and vice versa. This result indicates that the region is a particularly interesting one. We feel that these objects deserve further study.

3.4 Determination of the Distances of the Observed Stars

A. From trigonometric parallaxes. As a preliminary to examining the relation of extinction with distance, we cross-correlated all the Celescope observations with catalogs of known parallaxes. About 10% of the observed stars possess trigonometric parallaxes; most of these appear to be members of the Gould belt. Reliable parallaxes extend only to 0.7 kpc.

B. From MK spectral class and apparent magnitude. For the B stars with MK spectral classes, one can deduce their distances by the relation ($m - M = 5 + 5 \log d$) if color excesses are known. For such stars observed by Celescope, the maximum distance deduced by this means is ~ 2.5 kpc. We hope to utilize these distances in the further study of extinction as a function of distance.

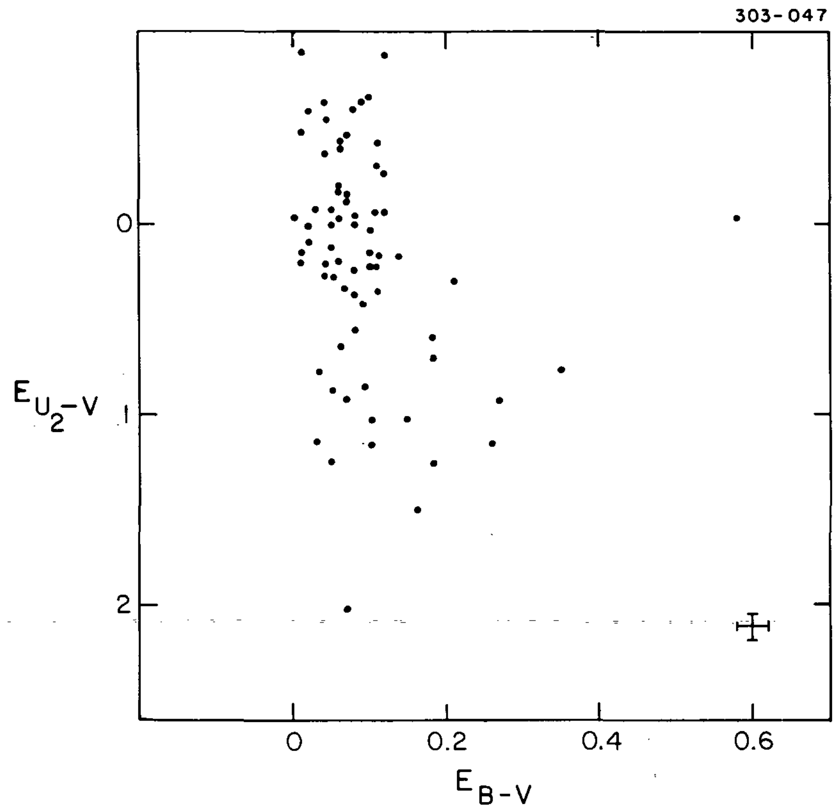

Figure 6. The noncorrelation of $E(U_2 - V)$ with $E(B - V)$ in Orion.

4. EXAMINATION OF SPECIAL OBJECTS OBSERVED BY CELESCOPE

4.1 Comet Tago-Sato-Kosaka

Reduction and examination of the pictures of this comet have revealed that its apparent nucleus acts as a point source. Its large Lyman-α halo extended to about 2°3, but its nucleus was no greater than 4 arcmin in diameter. This is in contrast to the previously estimated minimum of 30 arcmin.

4.2 Objects for Which No Ground-Based Identifications Exist

Examination of the 15 objects observed by Celescope for which no ground-based identifications could be made revealed that they were identifiable with faint stars on photographs. We should like to take a further look at these objects since they seem unusually bright in the ultraviolet. In particular, one group near +60° at 23^h may be a very young cluster.

4.3 Objects Bright in U_4

30 Doradus was identified in the normal course of preparing the Celescope Catalog. It is only one of a number of objects excluded from the Catalog, however, because their ultraviolet magnitudes were anomalously bright. We should like to detect and examine this and other objects in the same category that were observed in U_4 (the passband of Lyman α). We feel that such objects are of great intrinsic interest and warrant further inspection and analysis.

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